The susceptibility of glacigenic deposits to liquefaction under seismic loading conditions: a case study relating to nuclear site characterisation in West Cumbria

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Abstract: Previous research has established a chronostratigraphy of glacial/deglacial events together with a lithostratigraphical framework for the Quaternary deposits of the Sellafield area in West Cumbria. The glacial record is dominated by sediments and landforms laid down during the deglaciation of the Devensian ice sheet. The Quaternary deposits are characterised by complex sequences resulting from oscillating ice sheet margins, changing glacial lake and outwash environments, relative sea level changes and glacio-tectonic deformation. The resulting deposits are comprised of sequences which possess a wide range of grain size, shape and sorting; some are normally consolidated and have very low to low *in situ* density. An understanding of the geotechnical behaviour of these deposits is critical during geological site characterisation studies for the design of new buildings and infrastructure on existing and proposed nuclear sites. The geotechnical engineering behaviour of a sequence of glacial deposits on the Sellafield nuclear site is evaluated together with their susceptibility to potential liquefaction under certain seismic load conditions. The evaluation identified that layers of very loose to loose deposits within the ice sheet marginal landsystem are particularly susceptible to liquefaction under specified seismic loading conditions that are required to be modelled by the UK Office for Nuclear Regulation (ONR).

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Geological site characterisation investigations have previously been carried out in West Cumbria for the Sellafield nuclear plant and by Nirex UK for the deep geological facility. Geological characterisation investigations continue to take place as part of the Sellafield nuclear decommissioning programme and are currently being undertaken as part of the NuGeneration nuclear new-build development investigations at the Moorside site, located immediately to the north-west of the Sellafield nuclear site. These investigations have included assessments of the engineering behaviour of Quaternary deposits in both static and dynamic load conditions. For any nuclear structure it is an important requirement to assess the effects of the seismic loading condition on the foundation materials supporting nuclear structures. Seismic loading is one of the basic concepts of earthquake engineering which means the application of an earthquake-generated agitation to a structure. Earthquake-generated agitation takes place at contact surfaces of a structure either with the ground or with adjacent structures. This paper provides some observations relating to the genesis of the glacial deposits on part of the Sellafield nuclear site area and the characteristics of the glacial landsystems in which they occur. The paper goes on to consider the geotechnical engineering behaviour of the glacial deposits together with their susceptibility to potential liquefaction under specified seismic load conditions required to be modelled by the UK

Office for Nuclear Regulation. The importance of the geological characterisation of the subsurface ground conditions, especially the Quaternary sequences in the Sellafield area, and in providing data for evaluating the liquefaction hazard is discussed.

Previous geological characterisation studies in the Sellafield area

Various nuclear site characterisation studies have been undertaken in the Sellafield area, West Cumbria. This research relates to the area centred on the Sellafield nuclear plant, Seascale. In 1991 Nirex chose an area near Sellafield as the focus for further investigations for a proposed deep geological facility, following preliminary geological investigations undertaken in 1989 (Nirex 1993, 1995, 1997a-d). The Nirex Science Programme intended to assess the suitability, or otherwise, of a site within the Sellafield area as the host for a deep geological repository for the disposal of intermediate and high level radioactive waste. The background to the site investigations at Sellafield were reported to the Yorkshire Geological Society (Michie & Bowden 1994; Bowden *et al*. 1998). A series of papers covering the geology and hydrogeology of the Sellafield area were published in the *Quarterly Journal of Engineering Geology* in May 1996 (Chaplow 1996; Michie 1996; Sutton 1996; Bath *et al.* 1996; Littleboy 1996). These focussed on characterising the Sellafield geology in relation to understanding groundwater flow systems within the Sellafield area. The investigations of Quaternary deposits led to the recognition of 'domains' of distinct hydrogeological character, identified based on physical characteristics that may influence flow within domains (Nirex 1997a-d; Smith & Cooper 2004). Information from the Nirex studies was used to establish the geological characterisation and confirmed that the Quaternary deposits of the Sellafield area, including the study area, are extremely variable and have clast size components ranging through coarse-fine-grained gravel and sand, silt and clay grades (Michie & Bowden 1994; Nirex 1997a-d; Bowden *et al.* 1998; Cooper *et al.* 1999, Smith & Cooper 2004). There is considerable variability within the individual beds resulting in hydrogeological properties that vary significantly within a domain over relatively short distances (McMillan *et al.* 2000). A formal lithostratigraphy for the Sellafield District was completed by Merritt and Auton in the Nirex Science Report SA/97/045 (Nirex 1997d; Merritt & Auton 2000). This scheme is subsumed into the top-down lithostratigraphy for the whole of the country (BGS 2011; McMillan & Merritt 2012). A simplified Quaternary sequence for the Sellafield Quaternary deposits was also described in a later BNFL report by Cooper *et al.* (1999). The prime reference for the event stratigraphy for West Cumbria with glacial reconstructions is Merritt & Auton (2000), and references therein). However, specific information on the glacial sequence across the Sellafield nuclear site area (including cross sections) are covered in Nirex Science Report SA/97/003 (Nirex 1997b).

Academic research has also been undertaken on the Quaternary history and resulting glacial deposits of the Sellafield area (Huddart 1991; Huddart & Clark 1994; Clark & Wilson 1994; Williams *et al.* 2001), which has identified a generalized sequence of ice sheet advance and later marginal oscillations based upon glacial depositional reconstructions, glacial stratigraphy and glacitectonic disturbance. Many exposures in the area are described in Browne *et al.* (1997). A useful summary of the Quaternary of the Sellafield district is provided by Stone *et al.* (2010).

Study Area

The study area is located 1 km north-west of the village of Seascale, Cumbria [NGR NY 034036], which is located on the edge of the West Cumbria coastal plain. It encompasses the entire Sellafield nuclear site and extends into the immediate local area, including the foreshore of the Irish Sea close to the confluence of the River Ehen and the River Calder, and the Moorside site located immediately to the north-west of the Sellafield nuclear site. The area is located on the northeastern margin of the Mesozoic East Irish Sea Basin in an area known as the Lakeland Terrace. The geology of West Cumbria is comprised of Carboniferous limestones and siliciclastic Triassic sandstones unconformably overlying a lower Palaeozoic volcanic sequence (Akhurst *et al*. 1997; Stone *et al.* 2010). The geology of the area is shown on the 1:50 000 geological maps, Sheet 37 (Gosforth), solid and drift edition (BGS 1999). The bedrock beneath the Sellafield site comprises the two uppermost units of the Triassic Sherwood Sandstone Group, namely the Scythian Calder Sandstone Formation and the overlying Anisian Ormskirk Sandstone Formation. These units represent thin, onshore extensions of a larger sedimentary basin that underlies the Irish Sea (East Irish Sea Basin). There is little or no record in the West Cumbria region of any sedimentary strata deposited after the Late Triassic until the Quaternary period, when the area was affected by several periods of glaciation. These events left a variable thickness of superficial deposits unconformably overlying the Triassic and pre-Triassic bedrock.

Glacial Record of West Cumbria

For wider context and an understanding of the variety of deposits that might occur at Sellafield, it is important to appreciate that the West Cumbrian region contains evidence of a complex Quaternary glacial history. Akhurst *et al.* (1997) initially proposed that the preserved deposits mainly relate to the last two main phases of glaciation, but Merrit & Auton (2000) identified evidence for several additional glacier marginal fluctuations (Figs. 1a, 1b & 2). Glacial deposits which pre-date the Last Glacial Maximum (LGM = MIS 2/3) of the Devensian Cold Stage are very patchy and such deposits (e.g., Drigg Till, possibly of MIS 6) occupy small basins in the rockhead. The stratigraphic architecture and depositional styles of the glacigenic deposits of the area are dictated by the intermittent infilling of the buried valleys of the precursor Ehen and Calder Rivers and the Gosforth lacustrine basin (Merritt & Auton 2000), into which subglacial and ice-proximal to distal sediments have been deposited, largely by the onshore-flowing Irish Sea Ice Stream, but also by west Lake District outlet glaciers (Fig. 2). Older deposits (post-dating the Drigg Till) laid down in the Gosforth lacustrine basin include glacilacustrine sediments of the Carleton Silt Formation (MIS 4?) and the overlying Glennoventia Formation (MIS 3), documenting a marine incursion at around 50 ka ^{14}C yrs BP.

Throughout the Devensian glacial stage, but more specifically during its later ice sheet maximum phase during MIS 2, also known as the Main Late Devensian or Dimlington Stadial, ice moving from the Lake District interacted with an ice stream in the Irish Sea Basin along the western and southern fringes of the region. This is evidenced by the complex interfingering and/or interstratification of Lake District and Irish Sea derived deposits, including the Blengdale, Aikbank Farm, Seascale and Gosforth Glacigenic formations. At Sellafield, particularly important depositional events were the Gosforth Oscillation and the Scottish Readvance, both of which involved the deposition and glacitectonic disturbance of sediments along a narrow coastal zone of West Cumbria. The sedimentary record of the Sellafield region is therefore particularly dominated by the products of warm-based, fast-moving ice streams and mountain-based outlet glaciers. In the Sellafield and Moorside areas much of the base of the ice sheet is likely to have been underlain by a deformable bed of water-saturated sediment, which would have facilitated rapid ice flow and widespread glacitectonite and subglacial traction till generation (*sensu* Evans *et al.* 2006; Evans 2018). Towards the ice margins, meltwater systems appear to have been effective in depositing extensive outwash sediments and glacial lake infills beyond the ice margin. The latter were particularly prominent where the Lake District and Irish Sea ice masses repeatedly separated over the west Cumbrian lowlands (Huddart 1994; Merrit & Auton 2000; Livingstone *et al.* 2012).

Following the Dimlington Stadial a major phase of de-glaciation occurred. There are several theories for the pattern of de-glaciation and the presence or absence of evidence for glacial re-advances in west Cumbria. However, it is generally accepted that, firstly, de-glaciation occurred sometime after 23 cal ka BP (Figs. 1a & 1b). This period entailed the retreat of the Lake District valley glaciers and the Irish Sea Ice Sheet from the west Cumbrian coastal plain and resulted in the widespread deposition of glacio-fluvial sequences pro-grading into proglacial/ice-contact lake deposits covering large parts of the coastal plain. The large lakes are thought to have developed on the coastal plain as meltwater became dammed against the retreating Irish Sea ice margin glaciers (Merritt & Auton 2000). Evidence from Nirex investigations (Nirex 1997b) indicated that these glacial meltwater deposits were subsequently overridden by later advances of ice, which resulted in thin till deposits that are locally extensive, but laterally discontinuous across the region. The Sellafield and Moorside region was affected by a sequence of glacial re-advance events during the de-glaciation (Nirex 1997b). The most extensive of these re-advances is referred to as the 'Gosforth Oscillation maximum' (about 21-19.5 cal. ka BP). During the period following this maximum re-advance, several smaller glacial advances and retreats may also have occurred. A final re-advance during the later stage of the glaciation, which Trotter *et al.* (1937) referred to as the 'Scottish Readvance' (about 16.8 cal ka BP), has been identified, but is considered to have only affected a narrow coastal zone. These glacial re-advances overrode substantial thicknesses of the older sediments that had accumulated following retreat of the Dimlington Stadial ice sheet and any deposits from the retreat phases of the previous re-advances. Hence, glacitectonic deformation and reworking of pre-existing deposits into ice-marginal lakes and meltwater networks was widespread.

The Quaternary glacial history of the Sellafield area is, therefore, characterized by a complex sequence of deposits representative of oscillating ice sheet margins, changing glacial lake and outwash environments, and relative sea level changes, superimposed locally by the imprints of glacio-tectonic deformation. The resulting late Quaternary stratigraphy of the Sellafield area is similarly complex, and commonly difficult to characterise in detail from isolated exposures and excavations.

Sellafield Quaternary Sequence

A simplified stratigraphical approach for interpreting the Quaternary sediments of the Sellafield area was proposed by Cooper *et al.* (1999) and is summarised in Table 1. This comprised a reconstruction of the sequence of the latest glacial events and associated depositional processes to be used as a framework to interpret the lithologies recorded on historical borehole logs (Nirex 1997a-d). Cooper *et al.* (1999) considered this the most suitable method for characterising glacial deposits that were known to contain complex and discontinuous sedimentary sequences and for which the available data was variable in both type and quality. This event-based stratigraphical framework allows the lithological and structural fabric of the glacial deposits to be appraised without the need to correlate individual lithologies between boreholes and other exposures.

Table 1. Generic description of Sellafield Quaternary Sequence (Cooper et al. 1999)

Sellafield Region Glacial Landsystem

Although the Cooper *et al.* (1999) scheme, summarised in Table 1, is intended to provide a simplified and, therefore, more practical classification of complex deposits, it is important that the localized complexity is not understated as a result, especially with respect to the till formations, which inevitably will include interbedded deposits of great variety such as glacitectonites (*sensu* Benn & Evans 1996; Evans *et al.* 2006; Evans 2018), subaerial mass flow diamictons (e.g., Boulton 1972; Eyles 1979; Lawson 1979, 1981, 1989; Eyles & Eyles 2000; Kjaer & Krüger 2001), and glacial lake-related subaqueous mass flow diamictons and ice-rafted stratified diamictons (e.g., Lowe 1976a, b; Eyles & Eyles 1984; Powell 1984; Nemec 1990; Mulder & Alexander 2001; Talling *et al.* 2012; Talling 2014). Indeed, true subglacial traction tills are always subordinate to these more variable facies (*sensu* Evans *et al.* 2006; Evans 2018). The expanding research base on glaciers and glaciation has led to the production of considerable volumes of data on the complexity of glacial processes and their resultant landforms and sediments (see Evans 2003, 2013, 2017 for reviews). Due to the great spatial and temporal complexity of glacial processes and landforms, glacial geomorphologists and geologists have found it appropriate to compile process-form models that relate to glaciation styles and dynamics. These landsystem models are useful for anyone embarking on characterisation studies or engineering surveys in glaciated regions. They should be regarded as broad templates for interpreting glacigenic landform-sediment associations by glaciation styles and ice dynamics in differing climatic and topographic settings (e.g., Evans 2017).

In lowland areas of complex ice sheet activity, such as the Cumbrian lowlands, the variety of process-form relationships responsible for glacigenic sedimentation has been summarized using a landsystems approach by Evans (2017). The models proposed for such settings are based upon recent refinements of glacial process-form relationships observed at modern glacier margins and as such serve as catalysts for more informed interpretations of the complex Quaternary stratigraphies recorded in places such as the Cumbrian lowlands. Relevant to the Sellafield area are the ice sheet-related landsystem and the subaqueous sediment-landform associations of Evans (2017).

The ice sheet-related landsystem comprises a subglacial footprint, ice-marginal complexes and supraglacial debris complexes. Within the ice-marginal complexes are extensive areas of glacilacustrine deposition and, hence, the occurrence of subaqueous sediment-landform associations. Glacigenic sediments, particularly tills, tend to thicken towards glacier and ice sheet margins due to the net advection or long-term transfer of subglacial materials from erosional to depositional zones beneath the ice by a variety of processes (Alley *et al.* 1997; Evans *et al.* 2006), referred to as 'till wave' development by Boulton (1996a, b, 2006). Where ice margins oscillate over the same area the terrain is underlain by varying thicknesses of glacigenic sediments, often comprising multiple subglacial tills whose local variability in composition and provenance is related to the reworking of local materials, ice flow directional changes or the subglacial erosion of fresh strata exposed by glacial over-deepening. This concept has been applied to the Irish Sea Ice Stream by Evans & Ó Cofaigh (2003) and similarly can be applied to the spatial patterns of glacigenic sediments on the Cumbrian coast, wherein more complex stratigraphies will result from oscillations of the ice margin, the migration of different glacier basal thermal regimes and lateral variations in flow conditions related to ice stream operation or variations in substrate geology and drainage. Ice sheet marginal lobes, such as those that have oscillated over the Cumbrian lowlands, are demarcated by a variety of arcuate belts of morainic assemblages, the internal characteristics of which are dictated by ice dynamics and substrate conditions. In soft-bedded substrates, such as those at Sellafield, the moraines typically comprise ice-thrust terrain (glacitectonic thrust terrain of the Scottish Readvance of Merrit & Auton 2000) and excavational basins or over-deepening's, where glacitectonic disturbance has led to the dislocation of sediment in the proglacial stress field (Aber *et al.* 1989; Van der Wateren 1995; Evans 2013). Overriding of formerly ice-marginal thrust masses will result in their streamlining or drumlinization to produce cupola hills (glacially overridden terrain inherent within Cooper *et al.* (1999) = Oscillation Till Formation). McMillan *et al.* (2000) also recognised a 'glacially over-ridden domain' when describing the hydrogeological characterisation of the Quaternary sediments at Sellafield. Complex and thick sequences of tills, often containing substantial bodies of glacitectonite, can form large arcuate moraine assemblages at the quasi-stationary margins of terrestrially-terminating ice streams due to the process of sub-marginal incremental thickening of till wedges (Evans *et al.* 2008, 2012). The glacitectonites are derived from the cannibalization of subaqueous sediment-landform associations and glacifluvial deposits laid down between ice advances.

The subaqueous sediment-landform associations that developed intermittently along the Cumbrian coast document former glacially-influenced proximal depo-centres (e.g., grounding-line fans, coalescent subaqueous fans and ice-contact deltas) and deposits typical of more distal settings (e.g., finer-grained, typically rhythmically bedded blankets and drapes). The proximal depo-centres are invariably linked directly to glacifluvial landforms (e.g., where esker networks link to subaqueous fans) or the subglacial traction zone (e.g., grounding zone wedges). Additionally, lateral and vertical facies variability results from the accumulation of advance and retreat depositional sequences. Important in this respect are the changes from subglacial to ice-proximal modes of sedimentation of diamicton, whereby tills may grade distally into subaqueous debris flow deposits; hence, ice-marginal oscillations will be recorded in glacitectonic structures, and the inter-digitation of subglacial and subaqueous deposits. Lateral and vertical facies changes are consequently complex, and diamictons often difficult to classify according to subglacial versus subaquatic origins.

Supraglacial debris complexes can be widespread where former englacial sediment loads were substantial. Because ice sheet margins, such as that represented by the Irish Sea Ice Stream in Cumbria, tend to overwhelm the underlying topography, their supraglacial debris load is derived predominantly from freeze-on at the bed and vertical transport by compressive flow, englacial folding and thrusting rather than from extraglacial sources such as surrounding rock slopes. In contrast, the lowland ice nourished by the Lake District ice dispersal centre will likely have carried more englacial and supraglacial debris, and, hence Lake District-derived glacigenic deposits should typically display more of the characteristics of supraglacial debris complexes. These include significant signatures of debris reworking due to the ubiquitous meltwater and mass flow processes associated with continuous topographic inversion (Eyles 1979; Kjær & Krüger 2001). The complex sedimentology of hummocky moraine and associated landforms reflects this dynamic depositional setting, and records multiple cycles of redeposition. Typically, the landforms contain inter-bedded debris flows and other mass-movement deposits, laminated lacustrine sediments, and glacifluvial sands and gravels, all displaying varying degrees of disturbance (Eyles 1979; Johnson *et al.* 1995; Andersson 1998).

Geotechnical properties of glacigenic diamictons

Each of the above characteristic process-form regimes is responsible for a range of glacigenic diamicton sedimentation, only some of which produce true tills. The geotechnical properties of glacigenic diamictons are acquired as a result of a sequence of three groups of processes: those which operate during the phase of transport of debris by the glacier (typically subglacial shear and deformation; e.g., Iverson 2010; Iverson & Iverson 2001; Iverson *et al.* 2007; Evans *et al.* 2016); those which operate during the process of deposition (typically marginal freeze-on, melt-out and squeezing; e.g., Evans & Hiemstra 2005), and those which operate post-depositionally (typically mass flowage; e.g. Lawson 1979, 1981). These processes determine diamicton/till characteristics such as grain size distribution, state of consolidation stratification, and presence of joints and deformation structures, which are reflected in the parameters commonly characterised in geotechnical investigations. The properties of glacial deposits are acquired because of the processes of erosion and transport by the glacier and reflect the mineralogy of source rocks and the distance of transport. When glacial debris is deposited as till, these basic properties may be significantly changed by depositional processes. These processes determine the bulk density of the till and its state of consolidation; they may produce sorting in the till to change its grain size distribution and, thus, alter its Atterberg limit; and they affect the shear strength of the till and its permeability.

The engineering geologist/geotechnical engineer tasked with site characterisation within glaciated terrain will wish to know the likely surface and subsurface distribution of sediments, so that not only may the best site be chosen, but also so that suitable sources of fill or aggregate may be found and exploited. Difficulties arise particularly at the site characterisation stage, when it is required to assemble an overall picture of the three-dimensional layout of the sediments from several sources such as geophysical surveys, trial pits, trenches, and boreholes. This stage is often rendered extremely difficult by the variable nature of glacial sediments; ice sheet-marginal, ice-proximal subaqueous and supraglacial deposits are especially difficult in this respect, and so it is a great advantage to have a conceptual model to guide interpretation. With poor exposure between the few available sections, it is perhaps not surprising that stratigraphic work in glacigenic deposits often results in controversy. In addition to primary depositional complexity, the effects of post-depositional bulldozing and thrusting by ice advances and re-advances, and the cannibalization of pre-existing sediments must also be considered, resulting in a greater understanding of multiple diamicton and/or till stratigraphies.

Although the variation in the geotechnical parameters of glacigenic deposits as determined by standard *in situ* and laboratory tests is considerable, it is still possible to relate in a general way the geotechnical properties of glacial deposits to their mode of genesis. The depositional processes described above can be invoked to explain certain geotechnical properties of glacigenic sedimentary sequences. The grain size distribution of englacial debris is acquired during entrainment, transport and during supraglacial deposition. Therefore, the grain size distribution may be significantly modified; hence, within a given sedimentary unit, there may be considerable grain-size variation due to the wide range of glacial processes involved in producing it.

Subglacial tills tend to mirror the grain size distribution of the debris in transport, although the lodgement process may cause the nucleation of boulder clusters and the formation of stone pavements. In some cases, it appears the different grain size fractions are non-randomly distributed with respect to each other on a small scale, thus producing a potentially more compressible structure than in the case of a melt-out till. They tend to be heavily over-consolidated, although in their upper parts flow deformation at lower basal shear stresses near the glacier margin may remould a hitherto dense till to one of higher voids ratio (see Evans & Hiemstra 2005). Joint planes within them tend to be horizontal shear joints or stress-release joints, although vertical conjugate joint planes may occur.

Sediment gravity flow diamictons are characterized by considerable grain size variability. Their grading curves commonly show loss or gain of finer-grained particles, settling out of coarse-grained particles, and may show rapid vertical and lateral variation within one flow unit. They may be enriched in fines and lie on the lower part of the T-line or depleted in fines and align on the lower part of the T-Line (Boulton & Paul 1976). The complex history of drying out, wetting, freezing and thawing produces complex vertical joints and horizontal variations in their state of consolidation, although they are rarely heavily over-consolidated. Complex joint patterns are common, although major vertical joints tend to dominate except where segregation ice lensing has been important. Sequences dominated by sediment gravity flow diamictons (which tend to contain both permeable coarser-grained horizons and concentrations of finer-grained sediment and are often intimately associated with thick glacifluvial sequences) will show bulk properties rather different from sequences composed principally of subglacial tills.

Researchers have found that mass flow diamictons had generally lower bulk densities (mean 1.62 g/cc) than subglacial tills (1.9 g/cc). Regarding index properties, similar Atterberg indices will be exhibited by mass flow diamictons compared to those of subglacial tills. On a plasticity chart tills will fall close to the T-line whereas mass flow diamictons will exhibit much greater variation (Boulton & Paul 1976; Paul 1984). The state of consolidation of a mass flow diamicton is related to both its depositional and post-depositional history. In general, many mass flow diamictons are over-consolidated, with past maximum stresses of around 150-300 kN/m^2. This is often the result of post-depositional drying, which tends to affect mass flow diamictons due to their exposed positions on the crest of, and within local high points of the topography (Paul 1984).

Bulk permeability will be increased by the presence of continuous sand and gravel bodies and may create problems during excavations due to their water-bearing capacity. Permeable horizons will also act as sand drains and decrease consolidation times, whilst clay horizons will increase them. Compressibilities will be decreased by the presence of sand and gravel beds, and increased by the presence of clay horizons, while the rapid variations in the distribution and type of such features will cause problems of differential settlement.

Liquefaction potential assessment

Soil liquefaction is a major factor causing damage during earthquakes (Bardet 2003). A state of 'soil liquefaction' occurs when the effective stress of soil is reduced to essentially zero, which corresponds to a complete loss of shear strength. This may be initiated by cyclic loading (i.e., repeated changes in stress condition), for example, during earthquake shaking. In such conditions a soil in a saturated loose state, and one which may generate significant pore water pressure on a change in load, are the most likely to liquify. The effects of liquefaction on foundations of buildings, bridges, port facilities, dams and utilities can cause significant economic and human losses after earthquakes (Harmada *et al.* 1994; Liu & Dobry 1997; Idriss & Boulanger 2008). Liquefaction engineering research was largely initiated because of the devastating 1964 Niigata earthquake in Japan and the 1964 Good Friday earthquake in Alaska, USA. Since these two earthquake events, substantial progress has taken place, albeit mainly confined to improved ability to assess the likelihood of initiation (or 'triggering') of liquefaction in clean, sandy soils (Bardet 2003). However, over time researchers became increasingly aware of the liquefaction susceptibility of both silty and gravelly soils, and the importance of post-liquefaction stress and deformation behaviour (Youd & Perkins 1987; Zhang *et al.* 2004). Seed *et al.* (2003), in their keynote presentation at the 26th Annual ASCE Los Angeles Geotechnical Spring Seminar, defined the key elements of liquefaction engineering as follows:

1. Assessment of the likelihood of 'triggering' or initiation of soil liquefaction.
2. Assessment of post-liquefaction strength and overall post-liquefaction stability.
3. Assessment of expected liquefaction-induced deformations and displacements.
4. Assessment of the consequences of these deformations and displacements.
5. Implementation (and evaluation) of engineered mitigation, if necessary.

The first step in soil liquefaction engineering is the assessment of 'liquefaction potential' or the risk of 'liquefaction triggering.' Advances in this research area have been described by various authors (Youd *et al*. 2001; Seed *et al*. 2003; Idriss & Boulanger 2006). The case study described below focuses on this aspect of liquefaction engineering using data from the Sellafield nuclear site.

Liquefaction was defined in the proceedings of the NCEER (1997) workshop as the transformation of a saturated granular material from a solid to a liquefied state because of increased pore-water pressure and reduced effective stress, caused by a rise in pore-water pressure when water is unable to escape. The phenomenon is most often observed in saturated loose sandy soils. This is because loose sand tends to compress when a load is applied; dense sands by contrast tend to expand in volume or 'dilate'. A state of 'soil liquefaction' occurs when the effective stress of soil is reduced to essentially zero, which corresponds to a complete loss of shear strength. Cyclic loading occurs during earthquake shaking (e.g., repeated change in the stress condition) and when the soil is in a saturated loose state this will generate significant pore-water pressure, making it susceptible to liquefaction. As pore-water pressure rises a progressive loss of strength of the soil occurs as effective stress is reduced.

The effects of soil liquefaction on the built environment can be extremely damaging (Bardet 2003). For example, buildings whose foundations bear directly on sand or gravel which liquefies will experience a sudden loss of support, which will result in severe and irregular settlement of the building. This will cause serious structural damage, including cracking of foundations and damage to the building structure itself, or may leave the structure unserviceable afterwards, even without structural damage (New York State Geotechnical Engineering Bureau 2015). Where a thin crust of non-liquefied soil exists between building foundation and liquefied soil, a 'punching shear' type foundation failure may occur. The irregular settlement of ground may also break underground utility services. The upward pressure applied by the movement of liquefied soil through the crust layer can crack weak foundation slabs and enter buildings through service ducts and may allow water to damage the building contents and electrical services (Youd 1984).

Glacial sequence and geotechnical properties

The site area used for the liquefaction assessment is located within the Sellafield nuclear site. Cross-sections of the sequence of Quaternary deposits investigated in the Sellafield study area are shown on Figs. 8 and 9. The Quaternary deposits extend to approximately 23 m depth below ground (bgl) level and overlie the Calder Sandstone Formation. The sequence reflects a complex subglacial to predominantly subaqueous and subaerial ice-marginal depositional environment characterized by layers of very loose and loose sands and gravels; medium dense to dense sands and gravels; and silty and clayey sands and gravels with various interbedded layers of firm clay at varying depths. Most of the sands and gravels are water-saturated. This sequence is characteristic of what Cooper *et al.* (1999) classified as the Oscillation Till Sequence, representing the ice-proximal release of glacially transported material due to melting of ice after the Dimlington Stadial. The glacigenic diamictons comprise relatively loose, permeable material. The sequence is complex with conditions that are critical for seismic events, i.e. very loose to loose granular deposits which are saturated and thin layers of clay with low permeability impeding the dissipation of excess pore-water pressures induced by seismic action. Liquefaction is more likely to occur in loose to moderately saturated granular soils with poor drainage, such as silty sands and gravels containing impermeable sediments (Jefferies & Been 2015; Youd *et al.* 2001). During wave loading, usually cyclic undrained loading, such as seismic loading, loose sands tend to decrease in volume, which produces an increase in their pore-water pressures and consequently a decrease in shear strength, that is, a reduction in effective stress. Depending on the initial void ratio, the soils can respond to loading either by strain-softening or strain-hardening. Strain-softened soils, such as loose sands, can be triggered to collapse, either monotonically or cyclically, if the static shear stress is greater than the ultimate steady-state shear strength of the soils. In this case flow liquefaction occurs, where the soil deforms at a low constant residual shear stress. If the soil strain hardens, for example, in moderately dense to dense sand, flow liquefaction will generally not occur. However, cyclic softening can occur due to cyclic undrained loading, for example, earthquake loading. Deformation during cyclic loading will depend on the density of the soil, the magnitude and duration of the cyclic loading, and amount of shear stress reversal. If stress reversal does not occur, zero effective stress cannot occur and cyclic mobility takes place (Robertson & Fear 1995). The resistance of the cohesionless soil to liquefaction will depend on the density of the soil, confining stresses, soil structure (fabric, age and cementation), the magnitude and duration of the cyclic loading, and the extent to which shear stress reversal occurs (Robertson & Wride 1998)

The Standard Penetration Test (SPT) N-values carried out within the sequence of glacial deposits at the Sellafield site demonstrated variable relative densities. Significant bands of dense to very dense sand was present in boreholes predominantly below 11.0 m depth bgl. However, SPT N-values also indicated very loose deposits in some of the boreholes between 12.0 m bgl and 18.0 m bgl. Standard Penetration Test (SPT) N-values carried out within the top 11.0 m of the deposits consistently recorded areas of very loose and loose sands and gravels. Combined plots of SPT N-values derived from ground investigations (Fig. 3) show widespread areas or zones of very loose and loose Quaternary deposits. As discussed previously, these low relative densities are typical of an assemblage of sediment gravity flow and associated stratified subaqueous deposits derived from the *in-situ* deposition of mainly granular deposits from an ablating ice sheet into an ice-proximal or ice-contact setting.

Sellafield liquefaction assessments

The use of the Standard Penetration Test as a tool for evaluation of liquefaction potential is a widely used approach (Seed & Idriss 1971; Zhang *et al.* 2004). One of the most widely accepted and widely used SPT-based correlations is the 'deterministic' relationship proposed by Seed *et al.* (1984, 1985). This correlation is based on comparison between SPT N-values, corrected for both effective overburden stress and energy, equipment and procedural factors affecting SPT testing (i.e., $(N1)_{60}$ values) versus intensity of cyclic loading, expressed as magnitude-weighted equivalent uniform cyclic stress ratio (CSR). The relationship between corrected $(N1)_{60}$ values and the intensity of cyclic loading required to trigger liquefaction is also a function of the fines content. This method is the basis of the approach adopted by CIRIA R143 (CIRIA 1995) and Eurocode 8 (BS EN 1998-5 2004) for liquefaction potential assessment.

Another approach has been developed by Seed *et al.* (2003) to include a probabilistic basis to the correlations to provide insight regarding either uncertainty or probability of liquefaction. This approach presents the relationships between $(N1)_{60}$ values and the intensity of cyclic loading expressed as contours of probability of triggering or initiation of liquefaction (P_L) for P_L = 5%, 20%, 50%, 80% and 95%.

For the Sellafield case study, assessments of liquefaction potential which follow current design practices have been undertaken using SPT data from all exploratory holes available for the site area. The liquefaction potential assessment analyses were carried out using the following three different design methods:

1. CIRIA R143 (CIRIA 1995) design method.
2. Eurocode 8 (BS EN 1998-5 2004) design method.
3. Seed *et al.* (2003) design method.

The CIRIA and the Eurocode 8 methods provide 'deterministic' SPT-based correlations to assess the soil susceptibility to liquefaction. These 'deterministic' correlations give a pass or fail result for the evaluation of the risk of liquefaction. The Seed *et al.* (2003) method provides 'deterministic' and 'probabilistic' SPT-based correlations to assess the risk of liquefaction. This approach provides a pass or fail result as well as the associated probability of liquefaction (P_L).

The BNFL guidance document prepared by Principia Mechanica Limited (1983) defined the response spectra and design basis earthquakes to be used for seismic analysis at the Sellafield nuclear site. This corresponds to an annual probability of exceedance of 10^{-4} and 84.1% confidence level, based on statistical analysis of design spectra of vertical and horizontal components of motion for three categories of soil conditions at Sellafield. Therefore, the liquefaction assessment for the current study was carried out for a conservative earthquake event of magnitude (M) = 6.0 and a peak horizontal ground acceleration (a_{max}) of 0.25 g and 0.35 g in accordance with UK nuclear structures seismic design requirements at Sellafield.

It should be noted that an assessment of the seismic hazard in the UK was carried out by the British Geological Survey (Musson & Sargeant 2008), for the purposes of preparing the UK National Annex to BS EN 1998-1 and PD6698. This assessment provided UK seismic hazard maps of probable peak ground accelerations based on a deterministic assessment of seismic hazard for 1 in 450 and 1 in 2500 return period events. These maps show that the Sellafield area lies within a zone of maximum Peak Ground Acceleration (PGA) 0.02g and 0.04g for 475 and 2500-year return periods, respectively. Although the seismic model parameters presented in the current study can be considered conservative compared to standard design of seismic hazard assessment in the UK, the sensitivity of the nuclear structures normally requires more stringent design requirement and, therefore, the conservatism can be justified.

The results of the liquefaction assessments are shown in Figs. 4-7 using the deterministic correlations of the three methods (CIRIA 1995; Eurocode 8 BS EN 1998-5 2004; and the probabilistic approach of Seed *et al*. 2003). Diagrammatic illustrations of the SPT data and probability of liquefaction versus depth for the Quaternary sequence are presented in Figs. 8 & 9. The results of the assessments indicated a potential high risk for liquefaction for both horizontal ground acceleration events. Due to the variation of the ground and groundwater conditions across the site, differences in excess pore-water pressure dissipation can be expected. In such circumstances large differential settlements are highly probable during a seismic event of magnitude (M) = 6.0.

When liquefaction is determined to be a potentially serious hazard, an assessment of the available strength/stiffness (post-liquefaction residual strength) is required. During liquefaction the soil strength is affected by void redistribution resulting in a potential for large deformations to occur (Harmada *et al.* 1994). In such circumstances, engineered remediation measures are required to keep these deformations within the tolerable limits for the structure. Without ground treatment, analyses to determine stability and deformations need to be carried out for post-liquefaction strength based on residual strength (minimum undrained shear strength at steady state), although redistribution of pore-pressure or cavitation of the pore fluid may occur before this steady state strength is reached. The shear modulus can be much softer than the pre-liquefaction condition and the decrease in stiffness being more significant than the undrained strength loss. To prevent liquefaction (after a liquefaction potential has been identified), ground improvement is required to make the ground conditions more homogeneous and with a more uniform permeability (Huang & Wen 2015). The required ground treatment should normally be in the form of drains and densification of ground materials as follows:

- Drains: Introduction of drains (i.e., installation of Vibro Stone Columns) will prevent the risk of localised deformations under the layers with low permeability and will reduce lateral deformations (Scott *et al.* 2000; Kornan & Elgamal 2004).

- Densification: Improving the mechanical properties of soil materials is also required to lower deformations to values tolerable by the superstructure (Topolnicki 2004; Huang & Wen 2015).

Discussion

Because of the correlation between the formation of glacial deposits and their geotechnical properties, described above, an understanding of the genesis of a sequence of glacial deposits can be a valuable aid to civil engineering site investigations and geological site characterisation studies. The Quaternary sediments of the Sellafield and Moorside area are most varied and were deposited by processes and in environments during the Dimlington Stadial. These sediments include tills, and other, mass flow derived, glacigenic diamictons and outwash deposits comprising glacifluvial sands and gravels. The occurrence of potential glacitectonite (*sensu* Benn & Evans 1996; Evans *et al.* 2006; Evans 2018) has not been assessed due to the restricted borehole records and this is a not an insignificant shortcoming in an area that is dominated by glacitectonic deformation. The Dimlington Stadial sediments were locally deformed by glacitectonic processes, generally related to local re-advances of the ice sheet. By identifying the mode of genesis of a glacial depositional landscape and the sedimentary associations of which it is composed, and by applying the appropriate sedimentary model to it, it is possible, with the aid of a minimum of sub-surface information, to assess the spatial distribution of the component lithologies and the range of sediment characteristics. This is an exercise which is of great value during geological site characterisation. For example, it is suggested that an approach based on well-tried glacial sedimentological models enables a site investigation programme to be designed which is more likely to anticipate problems from changing sedimentary fabrics. Additionally, future facies assessments need to address the likely occurrence of glacitectonic disturbance and related glacitectonites, as they are significant in terms of lateral and vertical grain size variability, consolidation, fabric and structure (Benn & Evans 1996; Evans *et al.* 2006; Phillips *et al.* 2011; Evans 2018), but are difficult to appreciate and identify in borehole records.

The Sellafield and Moorside depositional landscape displays an ice sheet-related land-system comprising complex sequences of sand, gravel and silt, interdigitated with, and sometimes capped by, one or more mass flow diamictons. The superficial deposits comprise the Oscillation Till Sequence which overlies the Glacio-Fluvial Sequence or lies directly on the Calder Sandstone where the Glacio-Fluvial Sequence is absent (Cooper *et al.* 1999). The Oscillation Till Sequence is characterised by complex sequences of glacigenic mass flow diamictons interdigitated or interbedded with ice-proximal and ice-contact subaqueous and subaerial stratified sediments. These depositional process environments were typical of the glacial oscillations that affected the Sellafield area during and after the Dimlington Stadial. Glacitectonic disturbance and cannibalization was also widespread, but has not been directly recognized in the facies recorded in borehole logs apart from observations that the deposits are deformed. The deposits resulting from these processes comprise sequences which include normally consolidated material (i.e., not over-consolidated) and have very low to low *in situ* density. Locally the sediments possess a wide range of grain size, shape and sorting. Most are granular, and variations in their geotechnical engineering properties reflect differences in particle size distribution and shape. Deposits often display abrupt changes in lithology and consequently in relative density.

An understanding of the nature and behaviour of the Quaternary deposits is of fundamental importance in the geotechnical design process of nuclear structures and associated service infrastructure, particularly in the seismic condition. As has been shown in the case study, layers of very loose and loose deposits within the ice sheet marginal landsystem are particularly susceptible to liquefaction in the seismic loading condition. In such circumstances significant soil improvement would be required as part of foundation design to overcome the potential liquefaction problem of the very loose to loose granular deposits present within the glacigenic sequence.

Conclusions

Previous geological site characterisation investigations have been carried out in connection with the Sellafield nuclear plant decommissioning programme which commenced in the early 1980s, the deep geological repository by Nirex in the 1990s and, more recently, for the NuGeneration nuclear new build development site at Moorside. The research connected with these geological site characterisation investigations has helped to establish a chronostratigraphy of glacial/deglacial events together with a lithostratigraphical framework for the Quaternary deposits of the Sellafield area in West Cumbria.

The Quaternary deposits are characterised by complex sequences resulting from oscillating ice sheet margins, changing glacial lake and outwash environments, relative sea level changes and glacio-tectonic deformation. The nature of glacitectonic deformation and the occurrence of related glacitectonites is particularly significant in that considerable lateral and vertical complexity is introduced by such disturbances in glaciated terrain. The sequence of Quaternary deposits located on the Sellafield nuclear site was investigated extending to 23 m bgl and overlying the Calder Sandstone Formation. The sequence reflects a complex subglacial to predominantly subaqueous and subaerial ice-marginal deposition environment. The sequence is characterized by layers of very loose and loose sands and gravels, silty and clayey sands, and gravels with various interbedded layers of firm clay at varying depths. Most of the sands and gravels are water-saturated. This sequence is characteristic of the Oscillation Till Sequence (Cooper *et al.* 1999) and represents deposits associated with the ice-proximal release of glacially transported material due to melting of ice after the Dimlington Stadial.

The glacigenic diamictons comprise relatively loose and permeable material. The sequence is complex with conditions that are very critical for seismic events, that is, very loose to loose granular deposits which are saturated and thin layers of clay with low permeability impeding the dissipation of excess pore-water pressures induced by seismic action.

For the case study sequence, assessments of liquefaction potential which satisfied current UK nuclear design codes were completed using SPT data from representative boreholes through the sequence. The liquefaction assessment was carried out for an earthquake event of magnitude (M) = 6.0 and peak horizontal ground accelerations (a_{max}) of 0.25 g and 0.35 g in accordance with the UK seismic design requirements. Liquefaction potential assessment analyses were completed using three different methods (CIRIA 1995, Eurocode 8 BS EN 1998-5 2004 and probabilistic approach of Seed *et al.* 2003).

The results of the assessments indicated a potential high risk for liquefaction for both horizontal ground acceleration events. Due to the variation of the ground and groundwater conditions across the sequence investigated, differences in excess pore-water pressure dissipation can be expected. In such circumstances large differential settlement and ground deformation are highly probable during a seismic event of magnitude (M) = 6.0. In such circumstances, engineered remediation measures are required to keep these deformations within the tolerable limits for the proposed nuclear structures.

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Figure Captions

Figs 1a & 1b Palaeogeographical reconstructions for various stages of glaciation on the Cumbrian coast. Note: The dates provided in Figs 1a and 1b are derived from uncalibrated radiocarbon ages and must be interpreted with caution (reproduced with permission from Figs 8 & 9, Merritt & Auton 2000).

Fig 2 Maps showing: A) the Sellafield District showing locations of all Nirex QBH, BNFL Drigg (off-site) and Airbank Farm (AF) boreholes and lines of transect in the public domain (reproduced with permission from Fig 1A, Merritt & Auton 2000); and B) the generalized pattern of ice flow directions in northern England and southern Scotland (reproduced with permission from Fig 1B, Taylor *et al.* 1971).

Figure 3: Plot of combined SPT values for all boreholes within the study are glacial sequence (reproduced with permission from Sellafield Ltd.).

Figure 4: Plot showing the results of the liquefaction assessment based on the CIRIA R 143 Method (reproduced with permission from Fig 50, CIRIA, 1995).

Figure 5: Plot showing the results of the liquefaction assessment based on the Eurocode 8 Method (reproduced with permission from Fig B1, BS EN1998-5 2004).

Figure 6: Plot showing the results of the liquefaction assessment based on the Seed *et al.* (2013) Deterministic Method (reproduced with permission from Fig 17, *Seed et al.* 2003).

Figure 7: Plot showing the results of the liquefaction assessment based on the Seed *et al.* (2013) Probabilistic Method (reproduced with permission from Fig 16, Seed et al. 2003).

Figure 8: Geological cross-section 1 showing the results of the liquefaction assessment of the study area glacial sequence using a peak horizontal ground acceleration of a_{max} 0.25 g (reproduced with permission from Sellafield Ltd.).

Figure 9: Geological cross-section 2 showing the results of the liquefaction assessment of the study area glacial sequence using a peak horizontal ground acceleration of a_{max} 0.35 g (Reproduced with permission from Sellafield Limited).

Table 1. Generic description of Sellafield Quaternary Sequence (Cooper et al. 1999)

Made Ground
Anthropogenic materials due to excavation, construction and backfilling works, and in some areas can be of considerable thickness. The majority of made ground comprises disturbed, mixed and re-deposited natural ground, and a proportion of building debris (e.g., brick, concrete, tarmac, wood, wire and plastic).
Post-Glacial Sequence
All sediments deposited following the end of the last glaciation to the present day. During this period a key feature affecting deposition was relative sea level which both rose and fell considerably during this time in response to climatic and isostatic changes. The deposits are highly varied consisting of fluvial sands and gravels, river terrace deposits (gravels), clays, and silts

associated with overbank, lacustrine or estuarine type deposition, peat infilling hollows such as kettle holes, beach and sand dune deposits near the coast. Where they occur, these deposits form the ground surface and are particularly extensive along the coast, River Ehen valley and the original valley of the River Calder. In most areas this formation overlies the Oscillation Till Sequence, but where erosion has been particularly prevalent they may directly overlie older sequences and, in some cases, rest directly upon bedrock.
Oscillation Till Sequence
Extremely complex sequence encompassing several phases of oscillating ice sheet margins at the end of the Late Devensian. Consists of several laterally-discontinuous clayey diamictons (thin tills), separated and dissected by generally coarse-grained glacial outwash sediments, and contains deposits relating to the Gosforth Oscillation and possibly the later Scottish Readvance. It is common in many areas for tills from only one of these phases to be present due to either non-deposition or later erosion. From borehole evidence alone, distinguishing between the two tills is difficult due to the high lateral variation within them, the effects of palaeo-topography and glacitectonics. This sequence has been highly erosive in nature, probably removing and reworking older deposits. Across a large proportion of the Sellafield area this sequence forms the ground surface. The tills (clayey diamictons) can generally be described as mainly brown/reddish brown in colour, stiff, sandy, silty clays containing a few to some subrounded to subangular clasts from fine gravel to cobble size. The intersecting outwash deposits consist mainly of gravels, sand and gravels and coarse to medium grained sands. Where the tills are present at ground level they have often been weathered, causing fissuring and discolouration.
Glaciofluvial Sequence
Represents deposits relating to the deglaciation of the West Cumbria area immediately following the Dimlington Stadial and in many areas has eroded away the older glacial deposits, especially along channels, or valleys, present in the bedrock. Highly variable and consisting of gravels, sands and gravels and sands, with less common silts and clays. These deposits are very mixed, but rare broad fining upward sequences from gravels to fine-grained sands can be observed, especially near the top of the sequence. The clast constituents range from fine-grained gravel to cobble size and are subrounded to subangular in form, consisting mainly of local Borrowdale Volcanic Group and granitic clasts. The sands range from coarse-grained to fine-grained and may contain some gravel constituent. Generally, the coarse-grained sediments predominate towards the base of the sequence, representing deposition during the retreat, or melting, of the ice sheet and valley glaciers when large quantities of material would have been released from the ice. The top of the sequence represents the late stages of this glacial retreat when a lower energy environment prevailed, and finer material predominates. The occurrence of silts and clay is generally confined to the latter stages of the glaciofluvial sequence and may represent overbank, lacustrine or estuarine type deposits.
Lower Till Sequence
Glacial in origin and the depositional remnants of the Dimlington Stadial glaciation. This ice sheet is thought to have removed the majority of the pre-Late Devensian deposits from the area, as well as

a considerable thickness of bedrock. In the Sellafield area this deposit is generally only preferentially preserved in a few localities, immediately overlying bedrock. The sequence consists of a till, which is generally brown /reddish brown in colour, and commonly has a high percentage of mixed clasts from fine gravel (2-6 mm) to boulders, from rounded to angular in form, and dominated by local material such as the Borrowdale Volcanic Group sourced from Ennerdale and Eskdale.
Sandstone Bedrock (Calder and Ormskirk Sandstone Formations)
The underlying bedrock consists of the regional Triassic Calder and Ormskirk formations. Both are generally reddish brown in colour, fine-medium-grained and prone to weathering. For general interpretation purposes both sandstones have been grouped together under Sandstone Bedrock. The top of the bedrock is taken as being the top of the lithological rockhead, which in many areas is present as dense, reddish brown sand, representing completely weathered sandstone, overlying more competent strata.

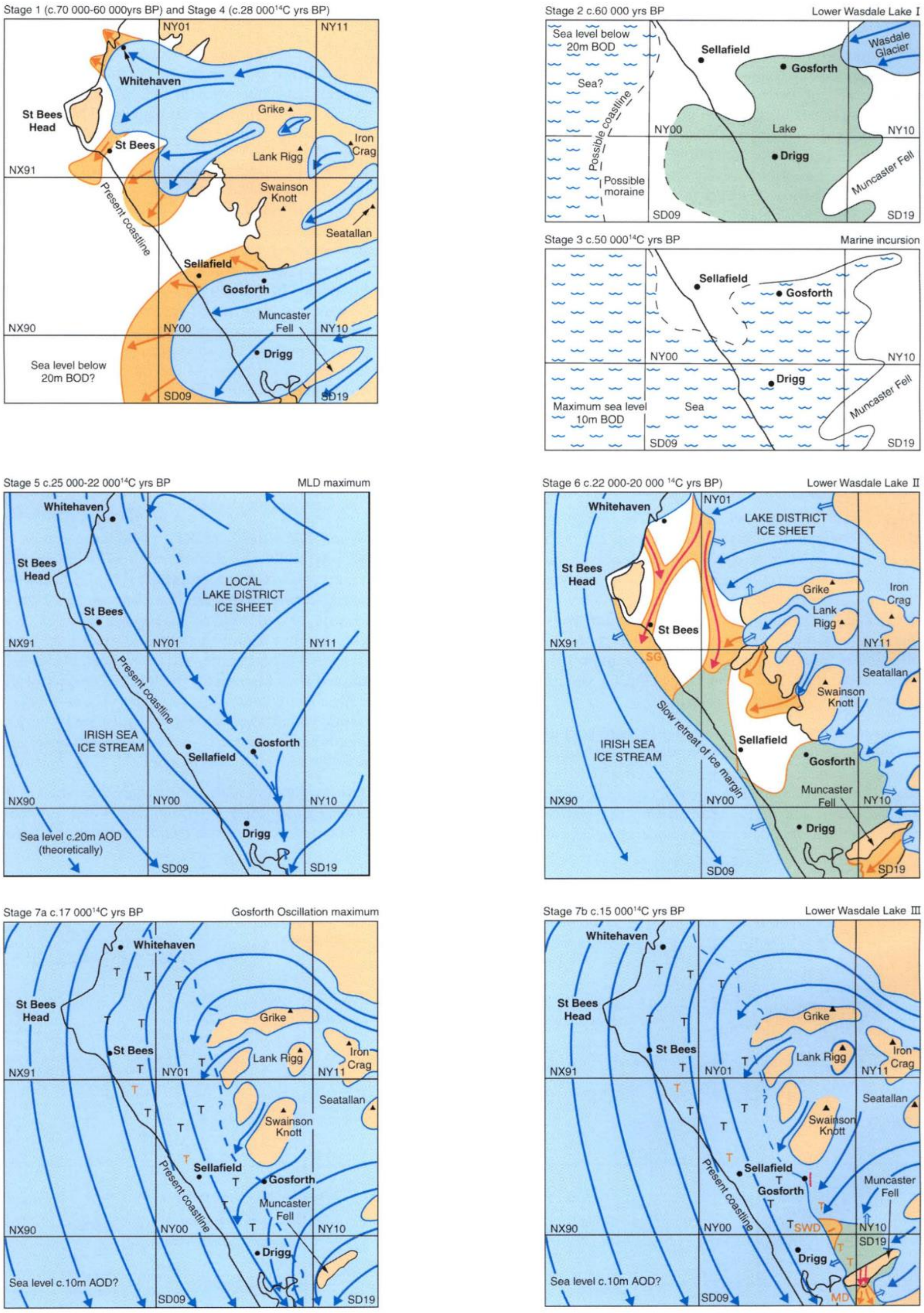

Stage 1 (c.70 000-60 000yrs BP) and Stage 4 (c.28 000¹⁴C yrs BP)
Whitehaven
St Bees Head
St Bees
Grike
Iron Crag
Lank Rigg
Swainson Knott
Seatallan
Present coastline
Sellafield
Gosforth
Muncaster Fell
Drigg
Sea level below 20m BOD?
NY01
NY11
NX91
NX90
NY00
NY10
SD09
SD19
Stage 2 c.60 000 yrs BP
Lower Wasdale Lake I
Sea level below 20m BOD
Sea?
Possible coastline
Possible moraine
Sellafield
Gosforth
Wasdale Glacier
Lake
Drigg
Muncaster Fell
NY00
NY10
SD09
SD19
Stage 3 c.50 000¹⁴C yrs BP
Marine incursion
Sellafield
Gosforth
Drigg
Muncaster Fell
Maximum sea level 10m BOD
Sea
NY00
NY10
SD09
SD19
Stage 5 c.25 000-22 000¹⁴C yrs BP
MLD maximum
Whitehaven
St Bees Head
St Bees
LOCAL LAKE DISTRICT ICE SHEET
Present coastline
IRISH SEA ICE STREAM
Sellafield
Gosforth
Drigg
Sea level c.20m AOD (theoretically)
NX91
NY01
NY11
NX90
NY00
NY10
SD09
SD19
Stage 6 c.22 000-20 000 ¹⁴C yrs BP)
Lower Wasdale Lake II
Whitehaven
LAKE DISTRICT ICE SHEET
St Bees Head
Grike
Iron Crag
Lank Rigg
St Bees
SG
Seatallan
Swainson Knott
Slow retreat of ice margin
IRISH SEA ICE STREAM
Sellafield
Gosforth
Muncaster Fell
Drigg
NY01
NX91
NY11
NX90
NY00
NY10
SD09
SD19
Stage 7a c.17 000¹⁴C yrs BP
Gosforth Oscillation maximum
Whitehaven
St Bees Head
St Bees
Grike
Lank Rigg
Iron Crag
Seatallan
Swainson Knott
Sellafield
Gosforth
Present coastline
Muncaster Fell
Drigg
Sea level c.10m AOD?
NX91
NY01
NY11
NX90
NY00
NY10
SD09
SD19
Stage 7b c.15 000¹⁴C yrs BP
Lower Wasdale Lake III
Whitehaven
St Bees Head
St Bees
Grike
Lank Rigg
Iron Crag
Seatallan
Swainson Knott
Present coastline
Sellafield
Gosforth
Muncaster Fell
SWD
Drigg
MD
Sea level c.10m AOD?
NX91
NY01
NY11
NX90
NY00
NY10
SD09
SD19

Figure 1a

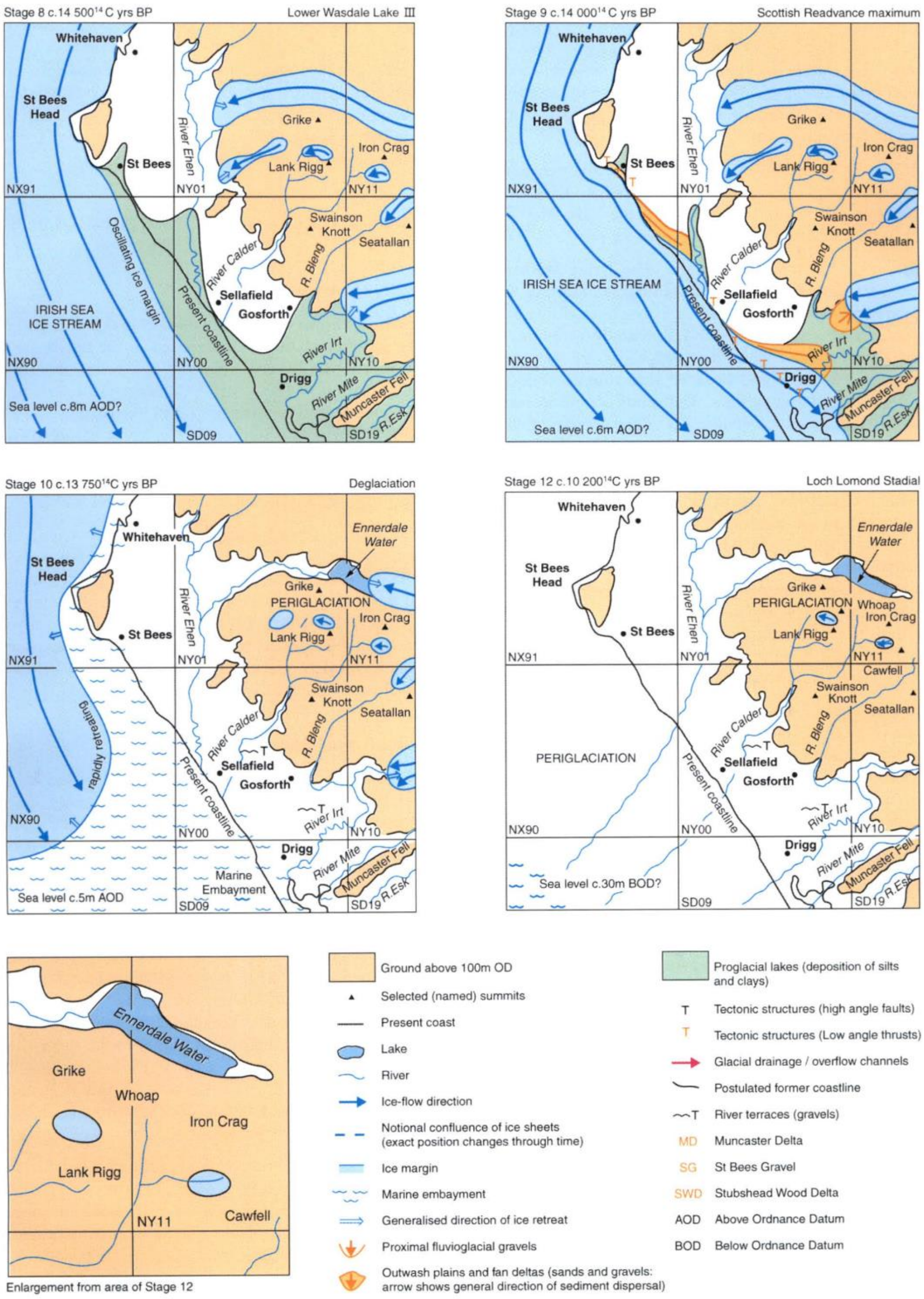

Stage 8 c.14 500¹⁴C yrs BP
Lower Wasdale Lake III
Stage 9 c.14 000¹⁴C yrs BP
Scottish Readvance maximum
Stage 10 c.13 750¹⁴C yrs BP
Deglaciation
Stage 12 c.10 200¹⁴C yrs BP
Loch Lomond Stadial
Whitehaven
St Bees Head
St Bees
IRISH SEA ICE STREAM
Oscillating ice margin
rapidly retreating
PERIGLACIATION
Sea level c.8m AOD?
Sea level c.6m AOD?
Sea level c.5m AOD
Sea level c.30m BOD?
Marine Embayment
Present coastline
River Ehen
River Calder
R. Bleng
River Irt
River Mite
R. Esk
Muncaster Fell
Sellafield
Gosforth
Drigg
Grike
Lank Rigg
Iron Crag
Whoap
Cawfell
Swainson Knott
Seatallan
Ennerdale Water
NX91
NX90
NY01
NY00
NY11
NY10
SD09
SD19
Enlargement from area of Stage 12
Ground above 100m OD
Selected (named) summits
Present coast
Lake
River
Ice-flow direction
Notional confluence of ice sheets (exact position changes through time)
Ice margin
Marine embayment
Generalised direction of ice retreat
Proximal fluvioglacial gravels
Outwash plains and fan deltas (sands and gravels: arrow shows general direction of sediment dispersal)
Proglacial lakes (deposition of silts and clays)
T Tectonic structures (high angle faults)
T Tectonic structures (Low angle thrusts)
Glacial drainage / overflow channels
Postulated former coastline
T River terraces (gravels)
MD Muncaster Delta
SG St Bees Gravel
SWD Stubshead Wood Delta
AOD Above Ordnance Datum
BOD Below Ordnance Datum

Figure 1b

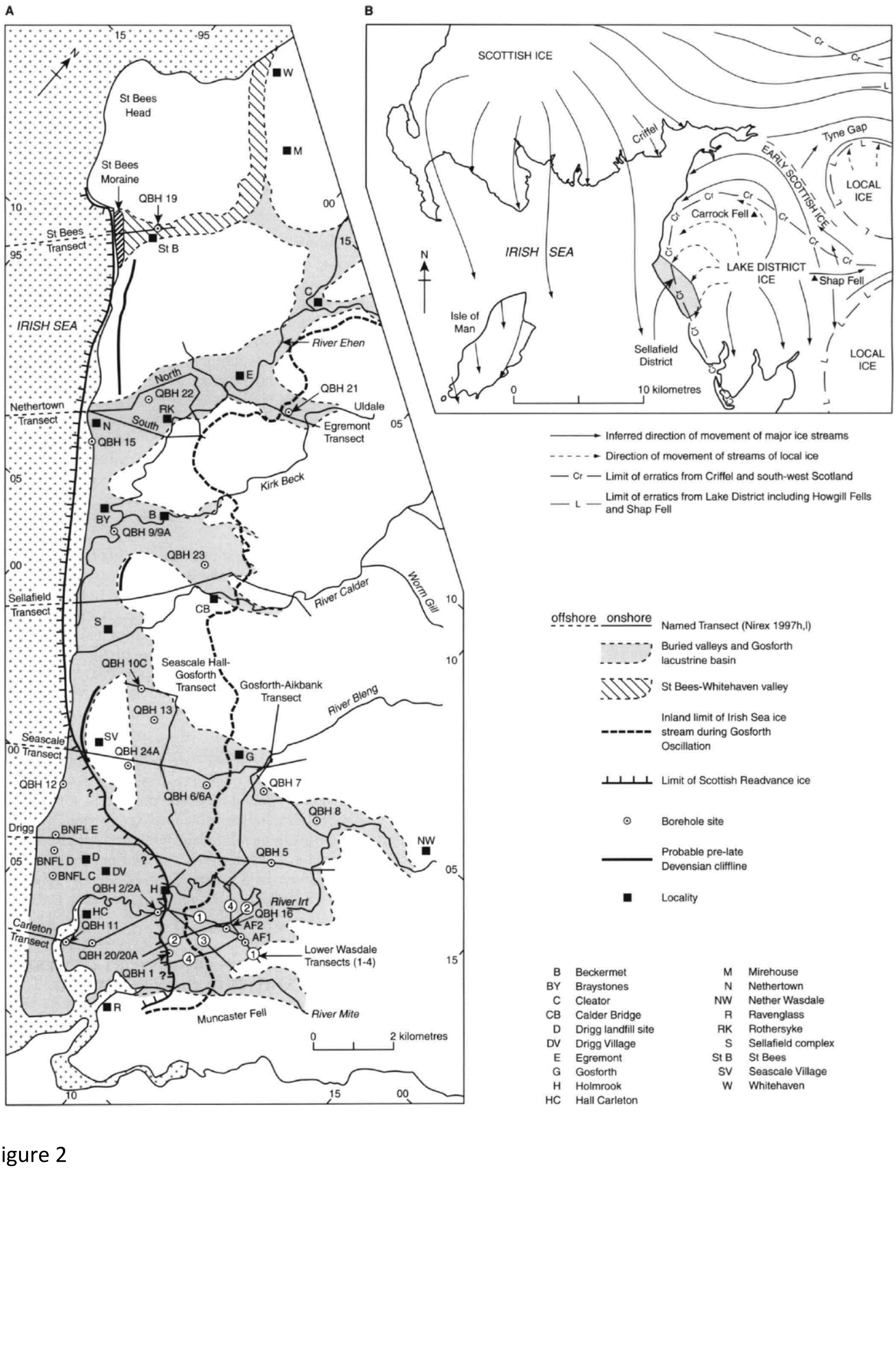
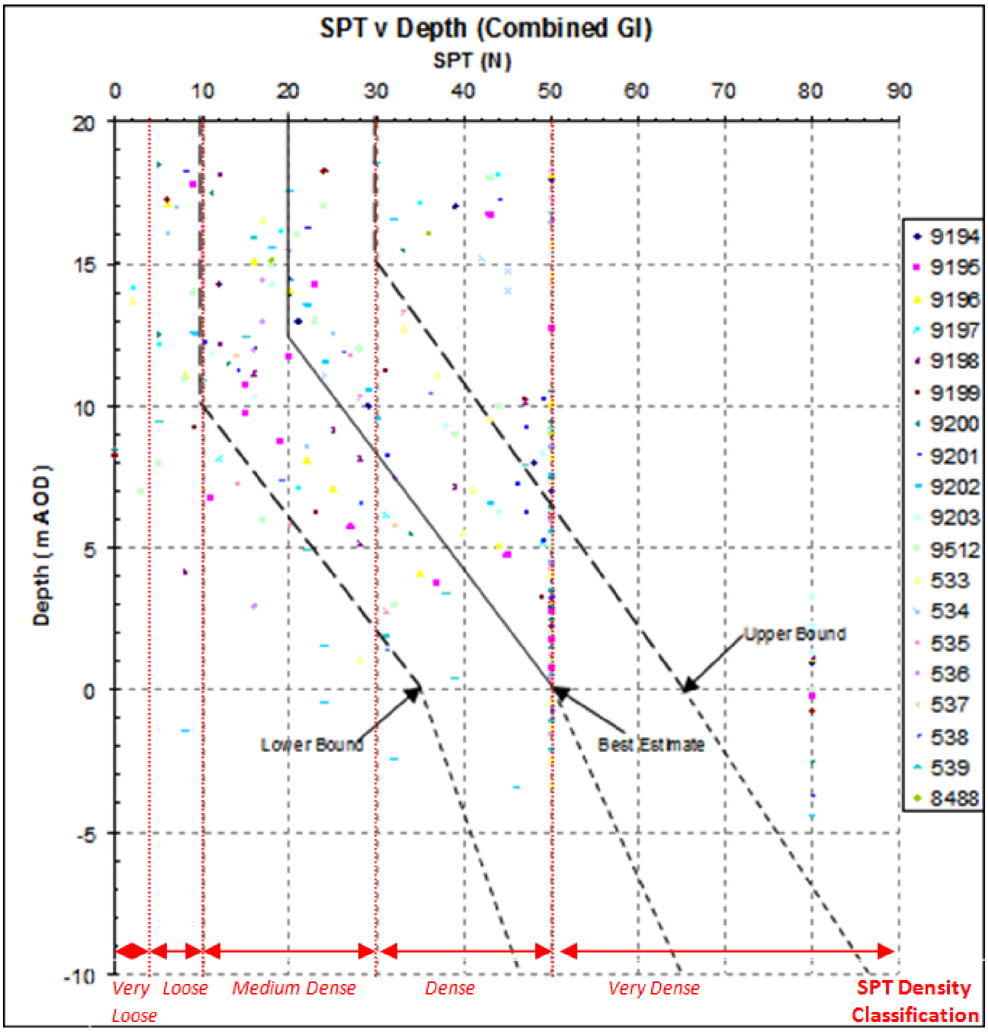

A
B
SCOTTISH ICE
IRISH SEA
Isle of Man
Criffel
Sellafield District
Tyne Gap
EARLY SCOTTISH ICE
LOCAL ICE
Carrock Fell
LAKE DISTRICT ICE
Shap Fell
LOCAL ICE
0 10 kilometres
St Bees Head
St Bees Moraine
QBH 19
St Bees Transect
St B
IRISH SEA
River Ehen
Nethertown Transect
North
South
QBH 22
RK
QBH 15
QBH 21
Uldale
Egremont Transect
Kirk Beck
BY
QBH 9/9A
QBH 23
Sellafield Transect
CB
River Calder
Worm Gill
QBH 10C
Seascale Hall-Gosforth Transect
Gosforth-Aikbank Transect
River Bleng
QBH 13
Seascale Transect
QBH 24A
QBH 12
QBH 6/6A
QBH 7
QBH 8
Drigg
BNFL E
BNFL D
BNFL C
QBH 5
QBH 2/2A
River Irt
QBH 16
AF2
AF1
Carleton Transect
QBH 11
QBH 20/20A
QBH 1
Lower Wasdale Transects (1-4)
Muncaster Fell
River Mite
0 2 kilometres
Inferred direction of movement of major ice streams
Direction of movement of streams of local ice
Limit of erratics from Criffel and south-west Scotland
Limit of erratics from Lake District including Howgill Fells and Shap Fell
offshore onshore Named Transect (Nirex 1997h,l)
Buried valleys and Gosforth lacustrine basin
St Bees-Whitehaven valley
Inland limit of Irish Sea ice stream during Gosforth Oscillation
Limit of Scottish Readvance ice
Borehole site
Probable pre-late Devensian cliffline
Locality
B Beckermet
BY Braystones
C Cleator
CB Calder Bridge
D Drigg landfill site
DV Drigg Village
E Egremont
G Gosforth
H Holmrook
HC Hall Carleton
M Mirehouse
N Nethertown
NW Nether Wasdale
R Ravenglass
RK Rothersyke
S Sellafield complex
St B St Bees
SV Seascale Village
W Whitehaven

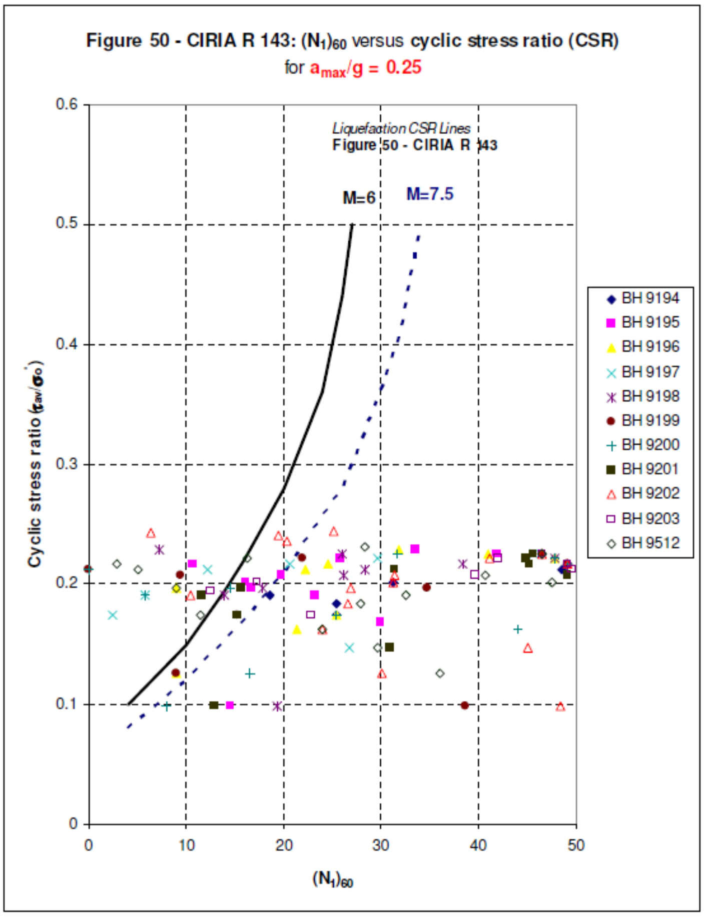
Figure 2



SPT v Depth (Combined GI)
SPT (N)
Depth (m AOD)
9194
9195
9196
9197
9198
9199
9200
9201
9202
9203
9512
533
534
535
536
537
538
539
8488
Upper Bound
Lower Bound
Best Estimate
Very Loose
Loose
Medium Dense
Dense
Very Dense
SPT Density Classification

Figure 3

CIRIA R 143 Method – 2011 New GI



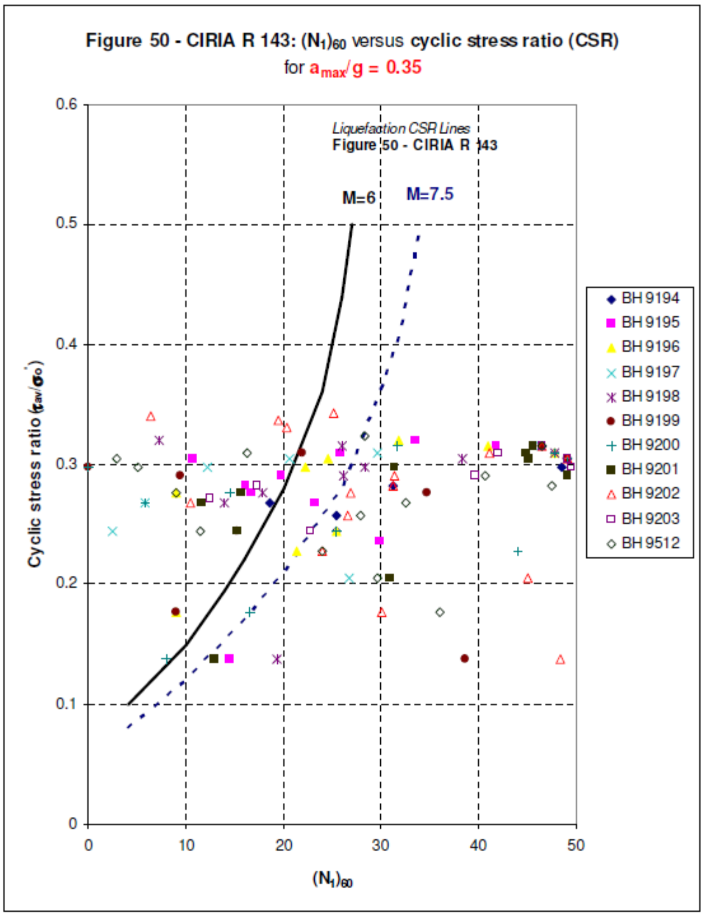
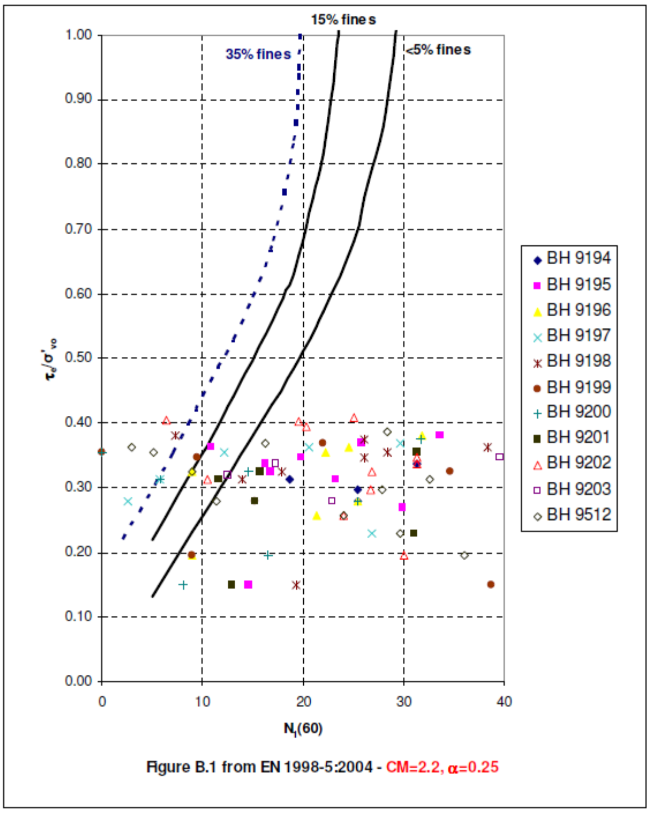


Figure 4

Eurocode 8 Method - 2011 New GI



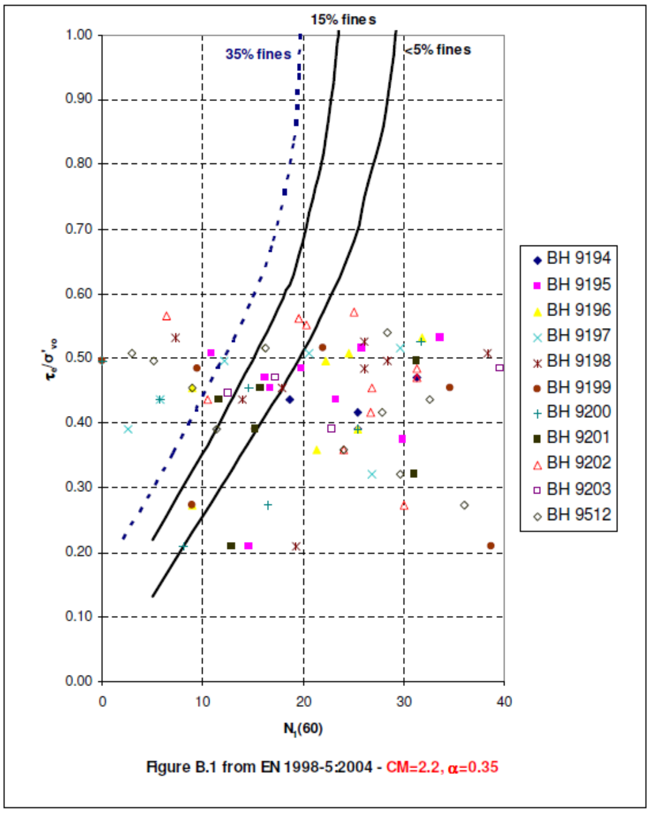


Figure 5

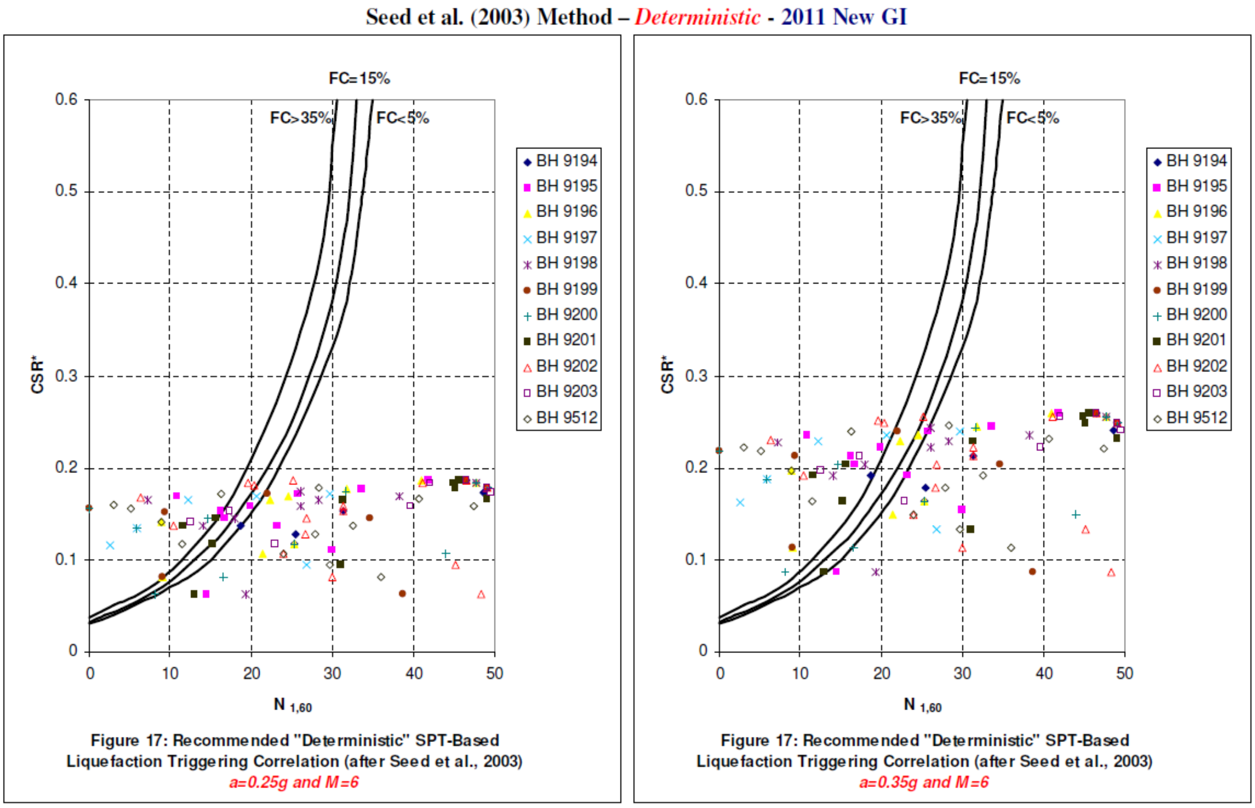

Seed et al. (2003) Method – Deterministic - 2011 New GI
FC=15%
FC>35%
FC<5%
CSR*
N 1,60
BH 9194
BH 9195
BH 9196
BH 9197
BH 9198
BH 9199
BH 9200
BH 9201
BH 9202
BH 9203
BH 9512
Figure 17: Recommended "Deterministic" SPT-Based Liquefaction Triggering Correlation (after Seed et al., 2003)
a=0.25g and M=6
a=0.35g and M=6

Figure 6

Seed et al. (2003) Method – *Probabilistic* - 2011 New GI

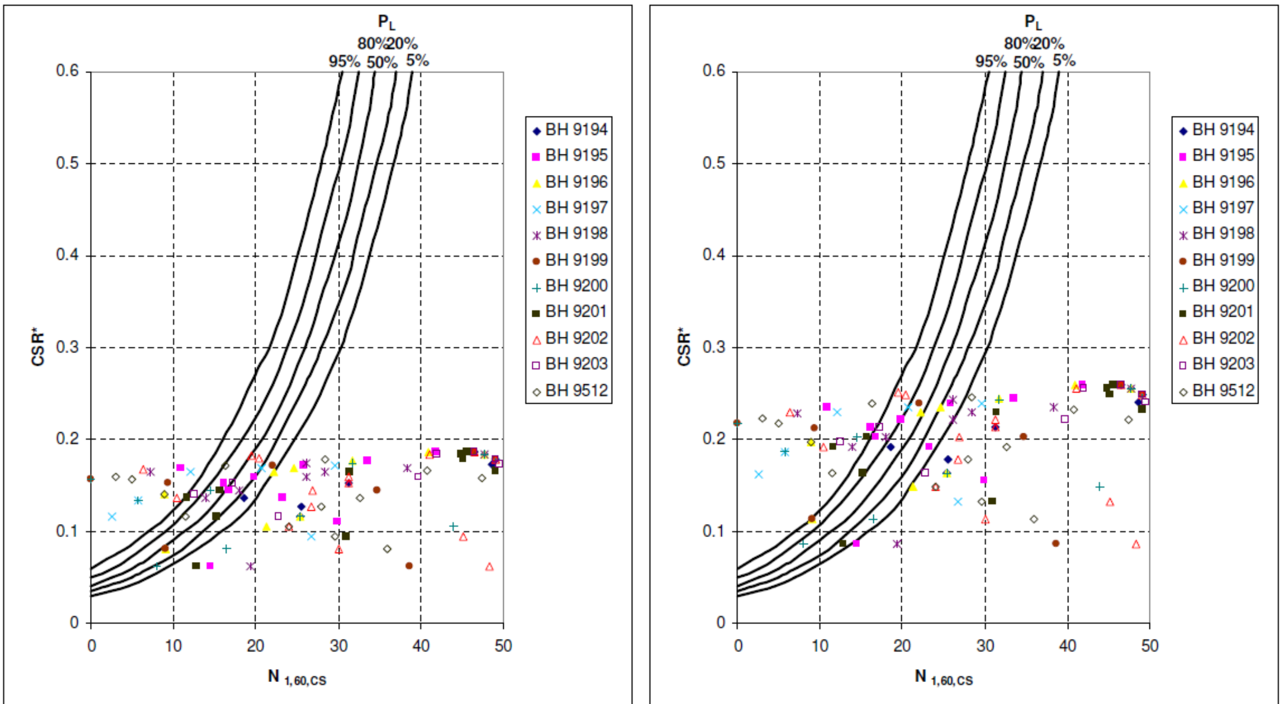
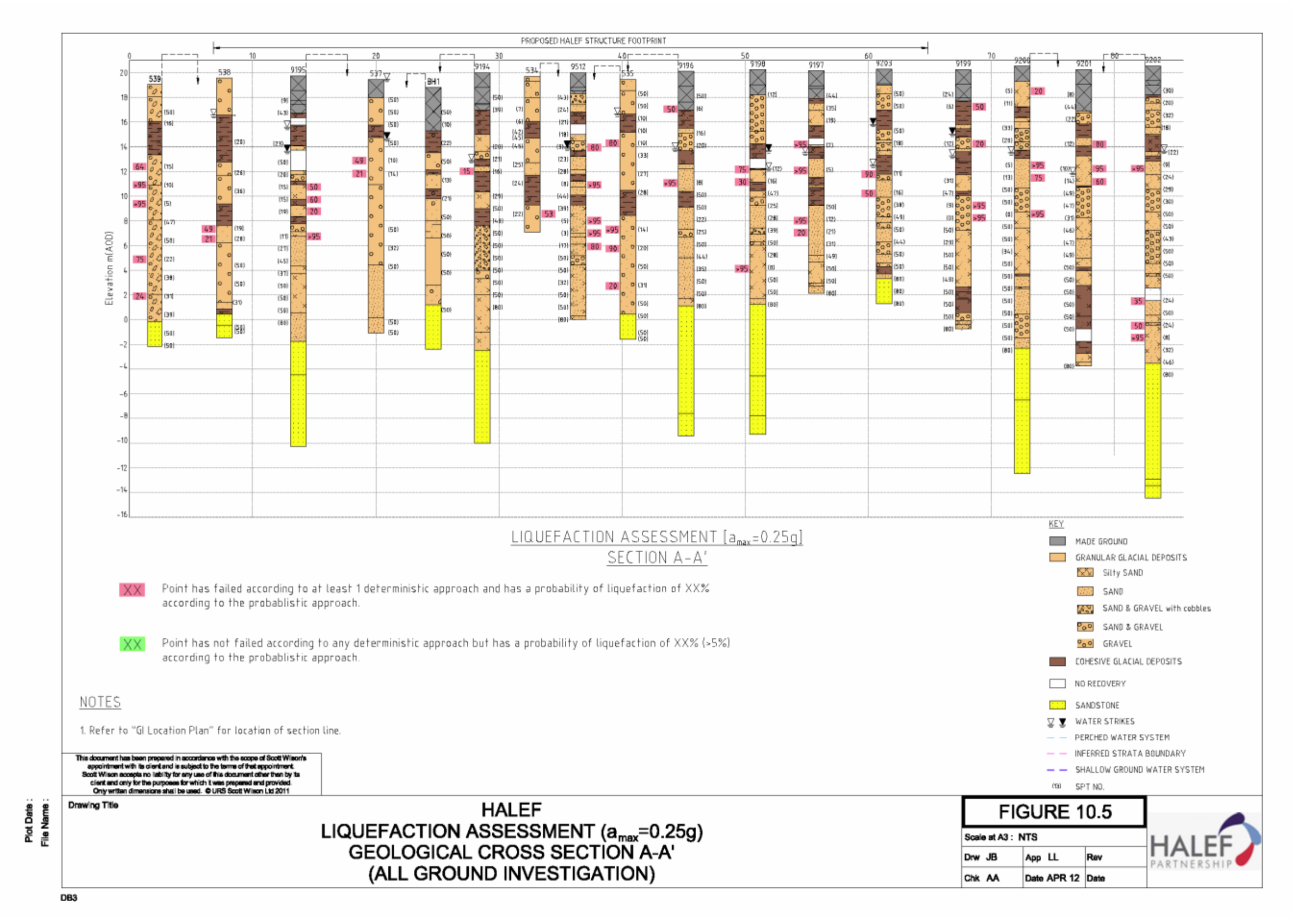


Figure 16: Recommended "Probabilistic" SPT-Based Liquefaction Triggering Correlation (after Seed et al., 2003)
a=0.25g and M=6

Figure 16: Recommended "Probabilistic" SPT-Based Liquefaction Triggering Correlation (after Seed et al., 2003)
a=0.35g and M=6

Figure 7


PROPOSED HALEF STRUCTURE FOOTPRINT
Elevation m(AOD)
LIQUEFACTION ASSESSMENT [a_{max}=0.25g]
SECTION A-A'
XX Point has failed according to at least 1 deterministic approach and has a probability of liquefaction of XX% according to the probablistic approach.
XX Point has not failed according to any deterministic approach but has a probability of liquefaction of XX% (>5%) according to the probablistic approach.
NOTES
1. Refer to "GI Location Plan" for location of section line.
KEY
MADE GROUND
GRANULAR GLACIAL DEPOSITS
Silty SAND
SAND
SAND & GRAVEL with cobbles
SAND & GRAVEL
GRAVEL
COHESIVE GLACIAL DEPOSITS
NO RECOVERY
SANDSTONE
WATER STRIKES
PERCHED WATER SYSTEM
INFERRED STRATA BOUNDARY
SHALLOW GROUND WATER SYSTEM
SPT NO.
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Plot Date :
File Name :
Drawing Title
HALEF
LIQUEFACTION ASSESSMENT (a_{max}=0.25g)
GEOLOGICAL CROSS SECTION A-A'
(ALL GROUND INVESTIGATION)
FIGURE 10.5
Scale at A3 : NTS
Drw JB
App LL
Rev
Chk AA
Date APR 12
Date
HALEF PARTNERSHIP
DB3

Figure 8

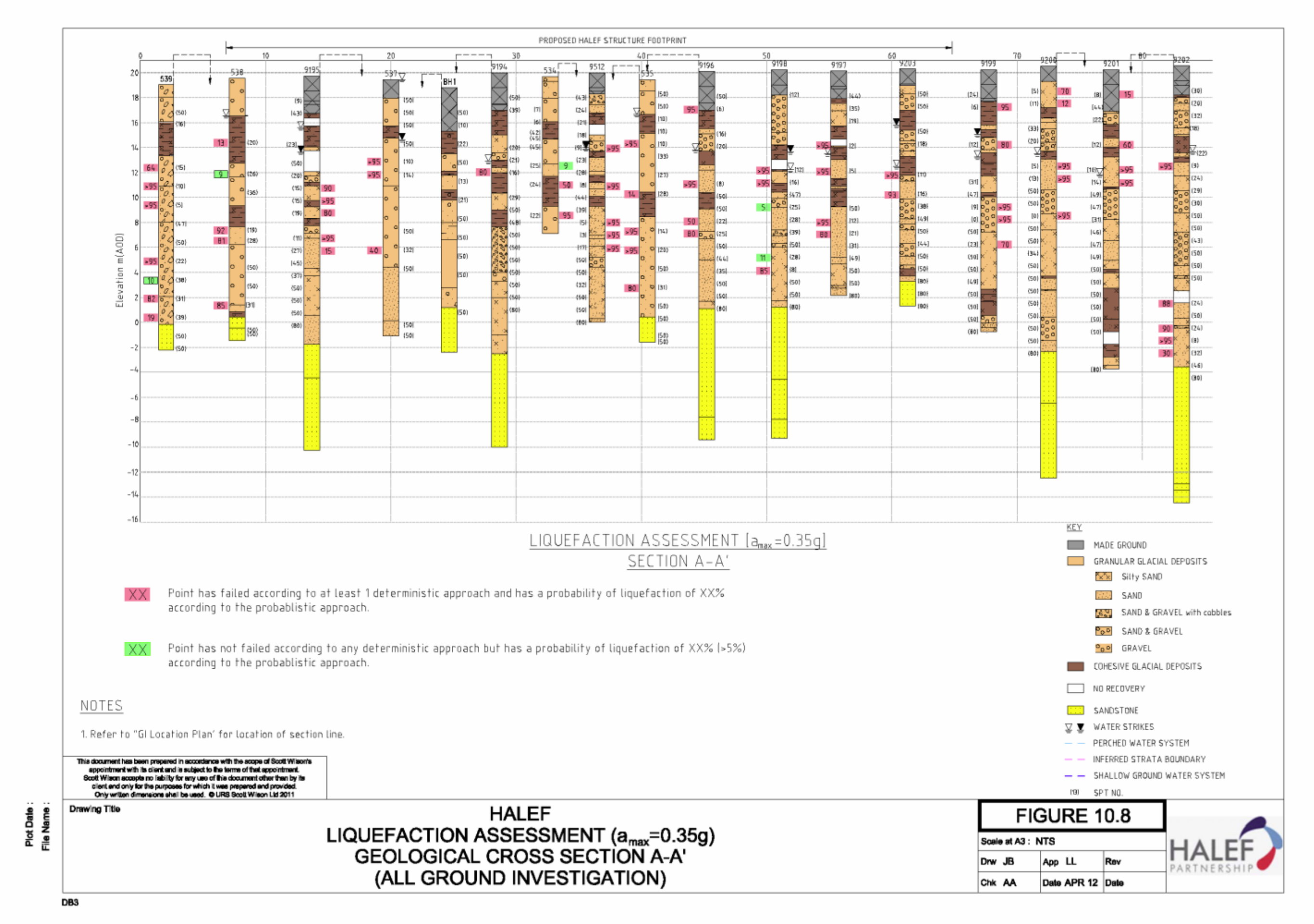
PROPOSED HALEF STRUCTURE FOOTPRINT
Elevation m(AOD)
LIQUEFACTION ASSESSMENT [a_{max}=0.35g]
SECTION A-A'
XX Point has failed according to at least 1 deterministic approach and has a probability of liquefaction of XX% according to the probablistic approach.
XX Point has not failed according to any deterministic approach but has a probability of liquefaction of XX% (>5%) according to the probablistic approach.
NOTES
1. Refer to "GI Location Plan" for location of section line.
KEY
MADE GROUND
GRANULAR GLACIAL DEPOSITS
Silty SAND
SAND
SAND & GRAVEL with cobbles
SAND & GRAVEL
GRAVEL
COHESIVE GLACIAL DEPOSITS
NO RECOVERY
SANDSTONE
WATER STRIKES
PERCHED WATER SYSTEM
INFERRED STRATA BOUNDARY
SHALLOW GROUND WATER SYSTEM
SPT NO.
Plot Date :
File Name :
Drawing Title
HALEF
LIQUEFACTION ASSESSMENT (a_{max}=0.35g)
GEOLOGICAL CROSS SECTION A-A'
(ALL GROUND INVESTIGATION)
FIGURE 10.8
Scale at A3 : NTS
Drw JB
App LL
Rev
Chk AA
Date APR 12
Date
HALEF PARTNERSHIP
DB3

Figure 9